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EMISSIONS ASSESSMENT OF JOHNSON MATTHEY CATALYZED WIRE MESH TRAPS

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1. SUMMARY

The emission test results for the Johnson Matthey catalytic trap oxidizer have shown the device to be an effective means for reducing diesel exhaust emissions. Although some sulphur dioxide to sulphate ($SO_4^=$) conversion was observed, all other emissions analyzed showed significant reductions. The catalytic trap oxidizer did not regenerate appreciably during the simulated mine cycle.

Limited regeneration during the MTU-LHD cycle suggests that further changes will need to be made to allow for practical operations of the Johnson Matthey catalytic trap in an underground mining environment. It is recommended that further tests be conducted over an LHD cycle with a higher average exhaust temperature to promote continuous regeneration. This condition would allow for a more practical assessment of typical machine operating emission characteristics.

2. INTRODUCTION

Diesel exhaust after-treatment devices, such as particulate traps, have been found to be effective in decreasing the general toxicity of diesel engine emissions. Johnson Matthey have developed a catalytic trap oxidizer (CTO) for this purpose. The CTO incorporates alumina coated wire mesh material as a substrate for the collection of particulate material. This substrate is coated with a catalyst and compressed to fit into a manifold container. In this application, the catalyst assists in the lowering of the ignition temperature (regeneration point) of the collected diesel particulate material. The greater the reduction in the ignition temperature the more acceptable the device will be from a mine vehicle application standpoint. In other words, vehicles with a low load factor duty cycle (low average exhaust temperature) require a particulate ignition temperature in the range of 300 to 350^{o}C.

The Johnson Matthey CTO is unique in that the trap takes place of the original engine manifold. This location is desirable from a regeneration viewpoint since exhaust temperature losses are kept to a minimum. Location of the trap in this manner may, however, pose some problems due to space restrictions in some vehicles and on the engine.

Results of a parallel program sponsored by the Ontario Ministry of Labour (MOL) showed that the Johnson Matthey CTO produced a primary ignition temperature of 332^{o}C with secondary ignition temperature in the range of 356^{o}C to 383^{o}C. It is suspected that the primary ignition temperature is a result of the partial oxidation of the soluble particulate fraction of the collected diesel emissions. Secondary ignition is suspected to occur at a temperature when the insoluble particulate fraction begins ignition. The secondary ignition was measured only during regeneration of the more heavily loaded traps.

In the MOL study, exhaust backpressures were measured over repetitive engine operation over the Michigan Technological University (MTU) load-haul-dump (LHD) cycle to characterize the exhaust backpressure building rates. Initial tests showed that the rate of backpressure rise was significantly different for the two traps (one per engine bank). The trap with the high backpressure increase rate was removed and repacked by Engine Control Systems (ECS). During the next series of tests the exhaust backpressure buildup still showed significant differences between the two traps. The individual traps also showed great variation in backpressure buildup rates from test to test. It was suspected that only limited regeneration was taking place.

During the above tests hot exhaust gas temperatures for cylinder No. 5 were noted. These eventually became too high to allow operation of the engine under full load. A great deal of time and effort have gone into diagnosing this problem, but as yet, the the cause of the problem has not been determined.

This report summarizes the work that was carried out to further evaluate the Johnson Matthey CTO as an approach to reducing diesel engine emissions in underground mining applications. The comprehensive emissions evaluation included determination of particulate control efficiency, gaseous emissions effects, sulfur dioxide conversion, aldehydes characteristics and effects on the exhaust emission mutagenicity.

3. DYNAMIC DYNAMOMETER TEST CELL

The following sub-sections describe some of the equipment used in the facility.

3.1 Dynamometer

An Eaton Model AO-8121 eddy current dynamometer is used in test cell #5 to absorb the power generated by the engine. This dyno is a wet gap type capable of absorbing 373 kW at 5000 RPM and has an inertia of 46 lb ft^2. Test cell #4 is equipped with a General Electric eddy current dynamometer. Torque is measured using a Lebow load cell connected to the trunnion mounted dynamometer casing. The dynamometer operation can be manually controlled in a speed or torque mode via a stand-alone dyno exitation controller. Dynamometer bearing lubrication is provided by gravity fed oil reservoirs. A Hayes-Dana driveshaft with rubber element absorption is used as a coupling between the engine and dyno.

3.2 Computer Control System

The heart of the dynamic test facility lies in the computer control system. This system uses a Hewlett Packard 1000 series E computer with 128K of memory and is coupled with a HP disc drive unit. Input/output interface is performed with Computer Products I/O equipment.

All programs are stored on a HP 7900 disc unit with measured and calculated data displayed on the operator console. The console is also used for entering operation commands concerning the test cell. During automatic control the system reads engine speed and torque ten times per second and, if required, corrects via output signals ten times per second. The system has a programming capability for cycle testing known as the schedule builder. The schedule builder is based upon a series of steps. A step is a defined RPM, torque, ramp time, stay time, where ramp time is the length of time to change from one load speed condition to the next. Stay time is defined as the length of time to remain at a given load speed. The minimum ramp time is one second and the minimum stay time is zero seconds. Up to 198 steps are user definable, however, the system includes the capability of major and minor looping within a cycle.

4. HEAVY DUTY DIESEL EMISSIONS TEST FACILITY

The sampling and measurement of diesel exhaust emissions has presented many problems with respect to obtaining representative data that will correlate to conditions that occur in the underground mining environment. Chemical and physical reactions with certain species of diesel exhaust emissions take place after the exhaust has been released from the engine exhaust system. Specifically, particulate agglomeration in the soluble and insoluble form occur as the exhaust temperature is lowered to promote condensation of the soluble organic material. Formation of nitrogen dioxide (NO_2) from nitric acid (NO) is a characteristic reaction in diesel exhaust as often it is released from the exhaust system. These reactions have necessitated the need for a representative diesel exhaust sampling and analysis system. EPA has standardized such a system for engine certification procedures.

In an effort to keep abreast of these changes, ORF has installed and commissioned a heavy duty diesel emissions test facility (Figure 1). The primary purpose of this facility is the measurement of emissions from diesel engines which are part of the dynamic test facility. The facility is comprised of two major systems; the dilution tunnel system and the analytical system. The following sub-sections describe these systems.

4.1 Dilution Tunnel System

There are basically two types of dilution tunnels available for the sampling of diesel exhaust emissions. One uses a single dilution method, the other a double dilution. ORF has selected a double dilution tunnel from a flexibility and cost standpoint. With a double dilution system the primary air mover can be down-sized considerably to meet the temperature criteria necessary in designing such a system. The system comprises of three basic sections as described below.

4.1.1 Dilution Tunnel

The dilution tunnel consists of 25.4 cm inside diameter primary tunnel and a 10.2 cm inside diameter secondary tunnel. All tunnel components are fabricated of stainless steel. Engine exhaust enters the primary tunnel via an upstream facing 10.2 cm nozzle. Dilution air flows past the nozzle and the resultant counter-current flow enhances mixing of the exhaust with the air. Figure 1 illustrates a schematic for the emissions test facility. The primary tunnel has been engineered to provide a Reynolds number of more than 4000 to provide sufficient turbulence of the diluted exhaust. A fine mesh screen prevents large foreign objects from entering the primary tunnel.

Three sample probes are located approximately 2.5 meters downstream of the exhaust inlet. The first probe is used to transfer a portion of the primary tunnel exhaust to the secondary tunnel. The second probe is used for sample transport to the heated hydrocarbon analyzer and the third probe is dedicated

to the other gaseous analyzers. Maximum allowable primary tunnel gas temperature at the sample probes is 190°C. A specially designed acoustic chamber was installed at the primary tunnel inlet to minimize engine exhaust and air mover noise in the vicinity of the test facility.

The secondary tunnel can be used to further dilute the sample from the primary tunnel to maintain a sample filter that will not exceed the maximum allowable 52°C. Three sample filters and one bypass filter are connected to the outlet of the secondary tunnel. The filter holders accept 70 mm diameter filters (Pallflex T60A20) and produce a 60 mm diameter stain area.

Secondary, or back-up filters, are used to remove any particulate material that has passed the primary filter. Any one of the four filters can be selected manually or automatically from the particulate console. Automatic sequencing of the filter is achieved using computer activated relays or using a programmable sequence timer.

The particulate console, contains an air pump and protective filters for sampling diluted exhaust. A second pump is used to provide pre-filtered air to the secondary tunnel when further dilution is required. Mass flows of sample gas and secondary dilution air are measured and controlled using mass flow controllers (Tylan Model FC202). These controllers are state-of-the-art devices which continuously monitor and correct the mass flow to maintain a proportional sampling rate, regardless of gas temperature and pressure. Accumulated dilution and sample gas flows are displayed using integrators, one set for each of the sample filters. The particulate console also contains a temperature measuring device to allow for recording of a variety of temperature stations, especially the primary and secondary tunnel gas temperatures.

4.1.2 Heat Exchanger

According to EPA specifications, the primary tunnel gas temperature must be adjusted to 43°C in order to provide constant gas density conditions to the primary air mover. In order to achieve a 147°C gas temperature drop, a tube and shell heat exchanger is located between the primary dilution tunnel and air mover. A 227 l pm water pump recirculates water through the shell side of the heat exchanger while primary tunnel exhaust gas is passed through the tube side.

During testing of duty cycles with high load factors, the primary tunnel gas temperature is well above 43°C. In these cases the heat exchanger is used solely to cool the gas and this is achieved by adding cold water to the recirculating water loop. Thermostatically controlled, air actuated, water valves allow water to enter the system and a check valve discharges an equal volume of warm water. A second heat exchanger which is steam heated can be used to raise the water temperature to 43°C (in the case of low load factor duty cycles).

4.1.3 Air Mover

The primary tunnel gas flow is normally maintained at 51.0 standard cubic meters per minute (SCMM) with a high capacity positive displacement blower. This blower is a roots type and uses a 22 kW electric motor as a drive. Excessive noise, characteristics of these blowers, is reduced using a Donaldson muffler.

4.2 Gas Analysis

The gas analysis system is comprised of a hydrocarbon console and a main analysis console. Filters, housed in the heated hydrocarbon console, are used to remove particulate matter from the sample gas stream. A Beckman, Model 402, heated hydrocarbon analyzer continuously measures gaseous hydrocarbons

(as methane) at a temperature of 190°C using a flame ionization detector. Background (ambient air) hydrocarbon concentrations are determined by sampling the dilution air at the primary tunnel. Concentrations of hydrocarbons in the dilution air are subtracted from the primary tunnel concentration to obtain hydrocarbon concentrations that are attributable to engine exhaust.

The main analysis console contains the NO, CO, CO_2 and heated NO_x analyzers. Two sample pumps are used to provide sample gas to the various analyzers. The following analyzers are used:

- NO_x - Beckman Model 955 heated chemiluminescent analyzer
- NO - Beckman Model 951A chemiluminescent analyzer
- CO - Beckman Model 867 non-dispersive infra-red
- CO_2 - Beckman Model 864 non-dispersive infra-red.

Three calibration gases are used to span each analyzer for a given concentration range. These gases can be selected by push buttons on the main analysis console front panel. Strip chart recorders are used to display analyzer outputs on a continuous basis. Heated lines are used to keep the sample temperature well above the gas dewpoint to minimize losses due to condensation. A Hankinson dryer, however, is used to remove sample gas moisture prior to the NO, CO and CO_2 analyzers to prevent water interference.

Recent additions to the HP 1000 computer software now provide the capability of recording all gaseous emissions data for steady state and cycle testing. The computer provides a printout of gaseous pollutant mass emissions and exhaust flows and can average results over a transient engine operating cycle.

4.3 Wet Chemical Methods

Sulphur dioxide and sulphate samples are taken using the controlled condensate sampling method with subsequent analysis using the barium sulphate turbidimetric method.

Aldehyde levels are determined by the 2-4, dinitroplynol hydrazone (DNPH) method with analysis by high performance liquid chromatograph. In both sampling procedures the samples are taken from the dilution tunnel.

5. JOHNSON MATTHEY CTO TESTING

Due to the lack of successful regenerations in the MOL test program, the Johnson Matthey traps were insulated by Engine Control Systems with an alumina silica ceramic fiber material to increase the retention of the trap temperature. Unfortunately, the insulation restricted the cooling air flow between the cylinders, so two inch extensions were added to the trap manifold connections by Engine Control Systems (see Figure 9). These extensions effectively placed the traps further away from the engine to allow less restricted cooling air flow.

Engine problems in test cell #5 necessitated the use of another test cell (cell #4) for the evaluation of the Johnson Matthey CTOs. The cell #4 General Electric dynamometer has a slightly slower response than the cell #5 Eaton dynamometer due to the inertia of the dyno. Although the MTU-LHD cycle has the same average values for both test cells the cell #5 is more dynamic. Hence, emissions data is not strictly comparable between the two cells due to two different engines and effects of dyno inertia. Figures 7 and 8 show a comparison of the MTU-LHD cycle between the two cells.

The engines used in both test cells are Deutz F8L 413 F/W air cooled diesel.

6. REGENERATIVE CHARACTERISTICS

Before beginning emission tests, the insulated traps were loaded with exhaust particulates at a low exhaust gas temperature (2200 RPM, 176 N.m) to collect material for an ignition temperature test. Figure 2 shows particulate

ignition taking place at approximately 365°C with no observable secondary ignition. This ignition temperature was 30°C higher than the earlier test with the insulated trap.

Figures 3 and 4 illustrate the pressure buildup rates observed during the emissions testing. These rates were so high that the traps could only be operated on the MTU-LHD cycle for two (2) hours before regeneration at full speed (2300 RPM), full load (576 N.m) was necessary. However, unlike earlier results the buildup rates were similar between traps and from test to test. Although there was limited cycle regeneration, the traps operated consistently and results were reproducible.

7. EMISSION RESULTS

LHD cycle emission results are from averaged data obtained during the MTU-LHD cycle. Burn-off data was averaged over the length of the regeneration at engine conditions of 2300 RPM and 576 N.m. The burn-off lasted from 10 to 15 minutes as observed by the exhaust backpressure.
The J-M catalytic traps proved effective in reducing concentrations of carbon monoxide (CO) and total hydrocarbons (THC). During trap buildup, as shown in Table I, 94% of CO and 83% of THCs were removed. Figures 5 and 6 graphically demonstrate that even during burn-offs only low concentrations of CO and THC peaks were observed. There were no observable effects of the traps on nitric oxide or total oxides of nitrogen (see Table 2). Nitrogen dioxide concentrations were measured to be lower with the traps installed although this may not necessarily be attributable to the traps. Tables I and II also illustrate the consistency of operation between the two traps.

The total particulate removal efficiency for the J-M traps was 85.6%. This consisted of 97.1% efficiency for soluble particulate and only 60.1% for the insoluble material. The traps were especially effective overall because the MTU-LHD cycle on the engine has a 69% soluble fraction. The soluble fraction was reduced to 14.1% during the cycle with the use of the traps. During

burn-off, the soluble fraction was only marginally higher at 26% (see Table 3). The pollutant mass emissions during burn-off are approximate averages because of heavy sulphate emissions collected on the sample filter and variability of burn-off length and intensity. However, during the 10 to 15 minute burn-off the average insoluble emissions are similar to baseline insolubles and soluble emissions are still 80% lower than the baseline solubles.

During the MTU-LHD cycle the traps were found to be storing 33% of the sulphate dioxide (SO_2), sulphate ($SO_4^=$) emissions (based on ppm concentrations) as shown in Table IV. The $SO_4^=$ concentrations were virtually the same with the traps (3.8 ppm) as baseline (4.5 ppm), while SO_2 was reduced from 34.7 ppm to 22.4 ppm.

For baseline emissions the % $SO_4^=$ was 11% of the total sulfur, however, during burn-off the % $SO_4^=$ constituted 39% indicating that much of the stored sulfur was released as $SO_4^=$ during burn-off conditions. These results indicate that conversion of SO_2 to $SO_4^=$ does occur during the MTU-LHD cycle and that the $SO_4^=$ is stored on the trap until regeneration conditions take place.

Total aldehyde emissions were reduced 74% (by mass) as shown in Table V. This series of tests exhibited greater aldehyde concentrations than previously found with this engine. Acetone in particular was significantly higher but no sources of contamination or analytical error were found. These high results may be due to the engine running rougher than during previous testing. The consistency between the reduction numbers for formaldehyde, acetaldehyde and acetone (82%, 82% and 77% respectively) support the fact that the traps reduce aldehydes in the 75% range during the MTU-LHD cycle.

The average value during burn-off compared to baseline was two-thirds lower for formaldehyde, approximately the same for acetaldehyde and approximately three (3) times higher for acetone.

Ames mutagenic testing was performed using the Salmonella tester strain TA-98 without metabolic activation. The baseline testing showed 12,529 revertants per m^3 raw exhaust for the Hi-Vol filter sample and 1,710 revertants per m^3 raw exhaust for the backup PUF. The catalytic traps showed only 681 revertants per m^3 for the Hi-Vol filter sample with negative mutagenic activity on the PUFs. During burn-off however, 24,177 revertants per m^3 were found. As shown in Table IV, revertants per ug of soluable material increased from 0.22 for baseline to 0.33 for buildup to 3.79 for burn-off.

8. CONCLUSIONS

The current form of the Johnson Matthey catalytic trap exhibits limited regenerative activity during the MTU-LHD cycle. In order to be practical, the trap will require testing over a hotter transient cycle or further improvements (i.e. improved catalytic material, fuel additives etc) to reduce its particulate ignition temperature.

The Johnson Matthey catalytic trap proved effective in reducing carbon monoxide, total hydrocarbons, total particulate and total aldehydes during the MTU-LHD cycle. Increases were found during burn-offs but were not of a significant nature. The traps exhibited sulphur dioxide to sulphate conversions during the cycle and stored this $SO_4^=$ on the trap. During burn-off, however, the stored sulphur emissions were released as sulphates.

From the wide range of Ames mutagenic results, it appears that the true evaluation of activity can only be obtained when the traps are operating in a constant regenerative mode.

The Johnson Matthey catalytic wire mesh traps were generally effective in reducing diesel exhaust emissions.

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TABLE I

Gaseous Emissions Averaged over MTU Cycle

Sample	Carbon Dioxide				Carbon Monoxide				Decrease	Total Hydrocarbons				Decrease
	%	g/h	g/kW.h	g/kg fuel	ppm	g/h	g/kW.h	g/kg fuel	%	ppm	g/h	g/kW.h	g/kg fuel	%
Baseline	5.7	67,100	961	3170	186	140	2.01	6.62		168	72.2	1.03	3.41	
JM Trap Combined Exhaust	5.8	66,500	918	3170	11	8.2	0.11	0.39	94%	29	12	0.17	0.58	83%
JM Trap Left Bank	5.9	67,600	935	3170	12	9.1	0.13	0.43		12	4.8	0.07	0.22	
JM Trap Right Bank	5.9	67,600	945	3170	17	12.6	0.18	0.59		13	5.5	0.08	0.26	

TABLE II

Gaseous Emissions Averaged Over MTU Cycle

Sample	Nitric Oxide				Nitrogen Dioxide				Total Oxides of Nitrogen			
	ppm	g/h	g/kW.h	g/kg fuel	ppm	g/h	g/kW.h	g/kg fuel	ppm	g/h	g/kW.h	g/kg fuel
Baseline	435	351	5.02	16.5	51	63	0.90	3.0	486	600	8.60	28.3
JM Trap Combined Exhaust	403	315	4.35	15.0	32	39	0.54	1.8	435	522	7.21	24.9
JM Trap Left Bank	457	179	4.96	16.8	34	20	0.56	1.9	491	295	8.17	27.6
JM Trap Right Bank	411	162	4.51	15.1	38	23	0.64	2.1	449	275	7.56	25.3

TABLE II! Particulate Mass Emissions

Test Condition	Soluble Particulates				% Removal	Insoluble Particulates				% Removal	Total Particulates				% Removal	% Solubles
	mg/m³	g/h	g/kW.h	g/kg fuel		mg/m³	g/h	g/kW.h	g/kg fuel		mg/m³	g/h	g/kW.h	g/kg fuel		
MTU Cycle Baseline	56.3	35.7	0.494	1.68		28.2	17.9	0.247	0.838		84.5	53.6	0.742	2.51		
	62.2	39.6	0.548	1.84		28.6	18.2	0.252	0.847		90.8	57.8	0.800	2.69		
	63.5	40.4	0.559	1.88		25.2	16.0	0.222	0.748		88.7	56.4	0.781	2.63		
Average	60.7	38.6	0.534	1.80		27.3	17.4	0.240	0.811		88.0	55.9	0.774	2.61		69.0
MTU Cycle JM Catalyzed Traps	2.42	1.51	0.021	0.072		11.1	6.90	0.096	0.328		13.5	8.40	0.116	0.400		
	1.00	0.62	0.009	0.030		10.8	6.75	0.093	0.321		11.8	7.40	0.102	0.351		
	1.49	0.93	0.013	0.044		11.8	7.32	0.101	0.349		13.2	8.20	0.114	0.393		
	2.29	1.47	0.020	0.069		10.6	6.81	0.094	0.319		12.9	8.30	0.115	0.387		
	*7.04	4.51	0.062	0.211		9.23	5.91	0.082	0.277		16.3	10.4	0.144	0.488		
Average	1.80	1.13	0.021	0.054	97.1	11.1	6.94	0.096	0.329	60.1	12.8	8.08	0.112	0.383	85.6	14.1
2300 RPM/ 138 kW Burnoff	9.44	6.55	0.046	0.174		27.1	18.8	0.133	0.501		36.6	25.4	0.180	0.675		25.8
	6.27	4.38	0.031	0.116		24.3	16.8	0.119	0.448		30.6	21.2	0.150	0.564		20.5
	18.5	12.8	0.091	0.342		50.9	35.3	0.250	0.939		69.4	48.2	0.341	1.28		26.7
	14.9	9.48	0.068	0.256		33.8	21.5	0.155	0.581		48.7	31.0	0.223	0.837		30.1
	10.9	6.93	0.050	0.187		29.4	18.7	0.135	0.506		40.3	25.7	0.185	0.693		27.0 / 26.0

* spurious result, not included in averages

TABLE IV SO_2 and SO_4 Mass Emissions

Test # and Test Description	Total Conc. ppm (SO_2 + $SO_4^=$)	Conc. in Raw Exhaust, ppm SO_2	ppm $SO_4^=$	mg/m SO_2	Emission Rates for SO_2 g/h	g/kW.h	g/kg fuel	Emission Rates for $SO_4^=$ mg/m^3	g/h	g/kW.h	g/kg fuel	%SO_2+ $SO_4^=$ Stored**
#1, MTU Cycle with traps	24.8	20.6	4.20	54.7	34.3	0.47	1.63	16.7	10.5	0.14	0.50	
#2, MTU Cycle with traps	28.6	24.5	4.10	64.9	40.7	0.56	1.94	16.3	10.2	0.14	0.49	33.0
#4, MTU Cycle with traps	25.3	22.3	3.02	59.1	37.1	0.51	1.76	12.0	7.53	0.10	0.36	
Average	26.2	22.4	3.77	59.6	37.4	0.51	1.78	15.0	9.42	0.13	0.45	
#3, 2300/100% burnoff	77.6	42.4	35.2	112	78.1	0.56	2.08	140	97.1	0.70	2.58	
#5, 2300/100% burnoff	84.7	56.2	28.5	149	103	0.74	2.75	113	78.7	0.56	2.09	
Average	81.1	49.3	31.8	130	90.8	0.65	2.42	127	87.9	0.63	2.34	
#1, Baseline cycle *	38.7	34.2	4.53	90.8	58.8	0.84	2.78	18.0	11.7	0.17	0.55	
#2, Baseline cycle	42.3	37.7	4.62	100	64.8	0.93	3.06	18.4	11.9	0.17	0.56	
#3, Baseline cycle	36.4	32.2	4.28	85.4	55.3	0.79	2.61	17.0	11.0	0.16	0.52	
Average	39.2	34.7	4.48	92.1	59.6	0.85	2.82	17.8	11.5	0.17	0.54	

* Note: Assumed SO_4 concentration because of suspected tap water contamination of sample

** Based on SO_2 + $SO_4^=$ Concentrations

TABLE V Aldehyde Concentrations Averaged Over MTU Cycle

Carbonyl Compound		Baseline			JM Traps			% Change	JM Traps Burnoff
		Test 1	Test 2	Average	Test 1	Test 2	Average		
Formaldehyde	µg/m³	17,600	17,200	17,400	3,800	2,300	3,050	-82	5,620
	ppm	14.1	13.8	14.0	3.04	1.84	2.44		4.50
Acetaldehyde	µg/m³	8,430	7,220	7,820	1,650	1,120	1,380	-82	7,610
	ppm	4.60	3.94	4.27	0.90	0.61	0.76		4.15
Acetone	µg/m³	27,600	285,000*	27,600	7,580	4,890	6,240	-77	72,700
	ppm	11.4	118	11.4	3.14	2.02	2.58		30.1
Isobutraldehyde + Methyl Ethyl Ketone	µg/m³	3,710	900	2,300	6,660	<160	3,330	+31	<160
	ppm	1.24	0.30	0.77	2.22	<.04	1.11		<.04
Crotonaldehyde	µg/m³	<160	<160	<160	380	<160	190	-	<160
	ppm	<.04	<.04	<.04	0.13	<.04	.07		<.04
Hexanaldehyde	µg/m³	<140	<140	<140	<140	<140	<140		<140
	ppm	<.04	<.04	<.04	<.04	<.04	<.04		<.04
Benzaldehyde	µg/m³	<160	<160	<160	<160	<160	<160		<160
	ppm	<.04	<.04	<.04	<.04	<.04	<.04		<.04
Total Aldehydes	µg/m³	57,400	52,900	55,200	20,100	8,310	14,200	-74	86,000
	ppm	31.4	29.4	30.4	9.43	4.48	6.96		38.8
% Formaldehyde of Total		31	33	32	19	28	21		7

* Suspect result, not used in totals

Test Condition Dilution Ratio	Baseline MTU Cycle 16.4:1		Build-up with Traps MTU Cycle 18.8:1		Burn-off with Traps 2300 RPM/100% Load 24.1:1	
	Hi-Vol Filter	PUF	Hi-Vol Filter	PUF	Hi-Vol Filter	PUF
mg/m^3 SOF	56.9	9.0	2.1		6.37	
Revertants/m^3 raw exhaust	12,529	1,719	681	negative	24,177	negative
Revertants/µg	0.22	0.19	0.33	negative	3.79	negative

* All tests performed with Salmonella Tester Strain TA-98 without metabolic activation

TABLE VI Summary of Ames Mutagenicity Data

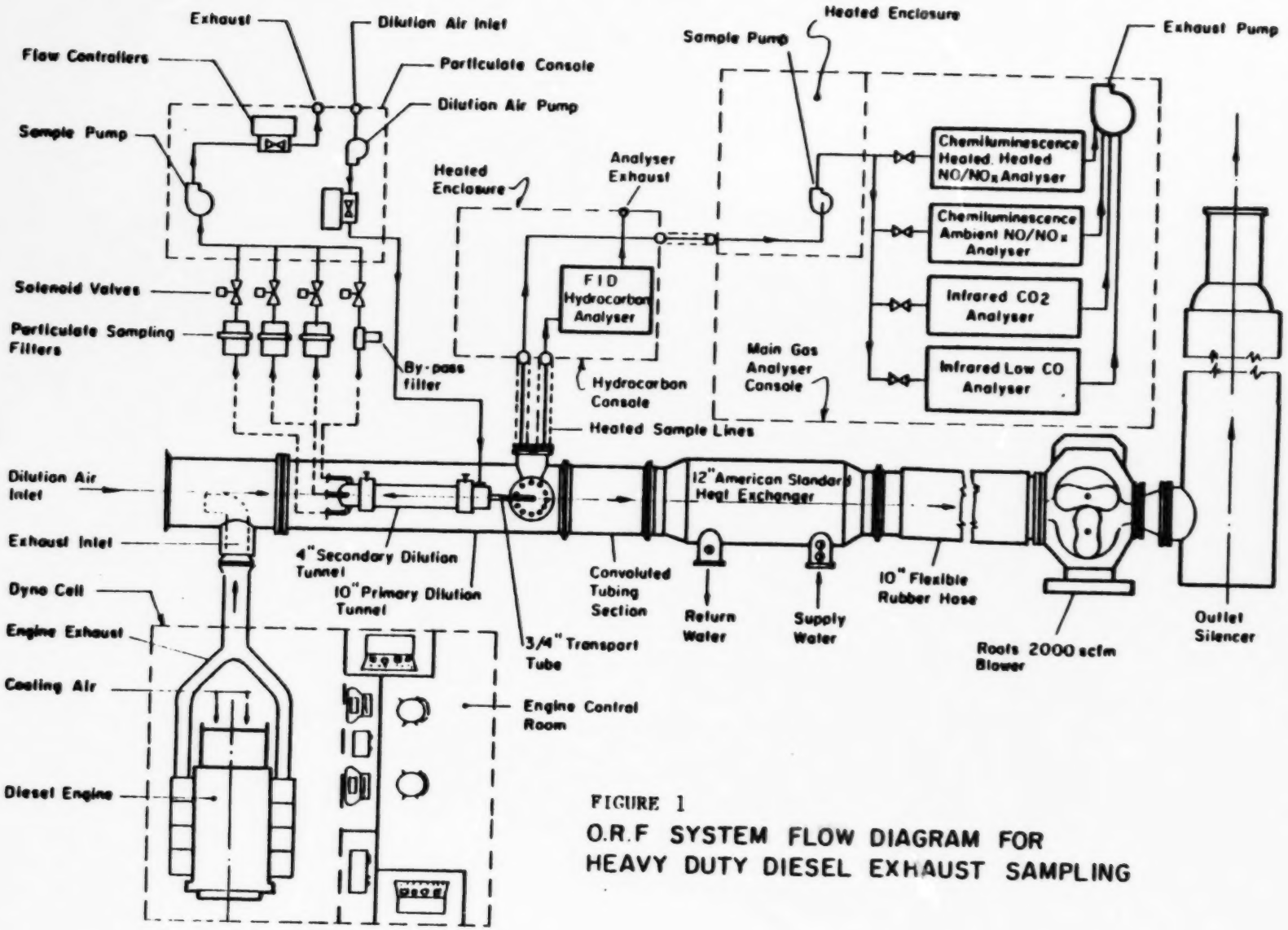


FIGURE 1

O.R.F SYSTEM FLOW DIAGRAM FOR HEAVY DUTY DIESEL EXHAUST SAMPLING

Figure 2: J-M CATALYZED TRAP IGNITION TEMPERATURE TEST

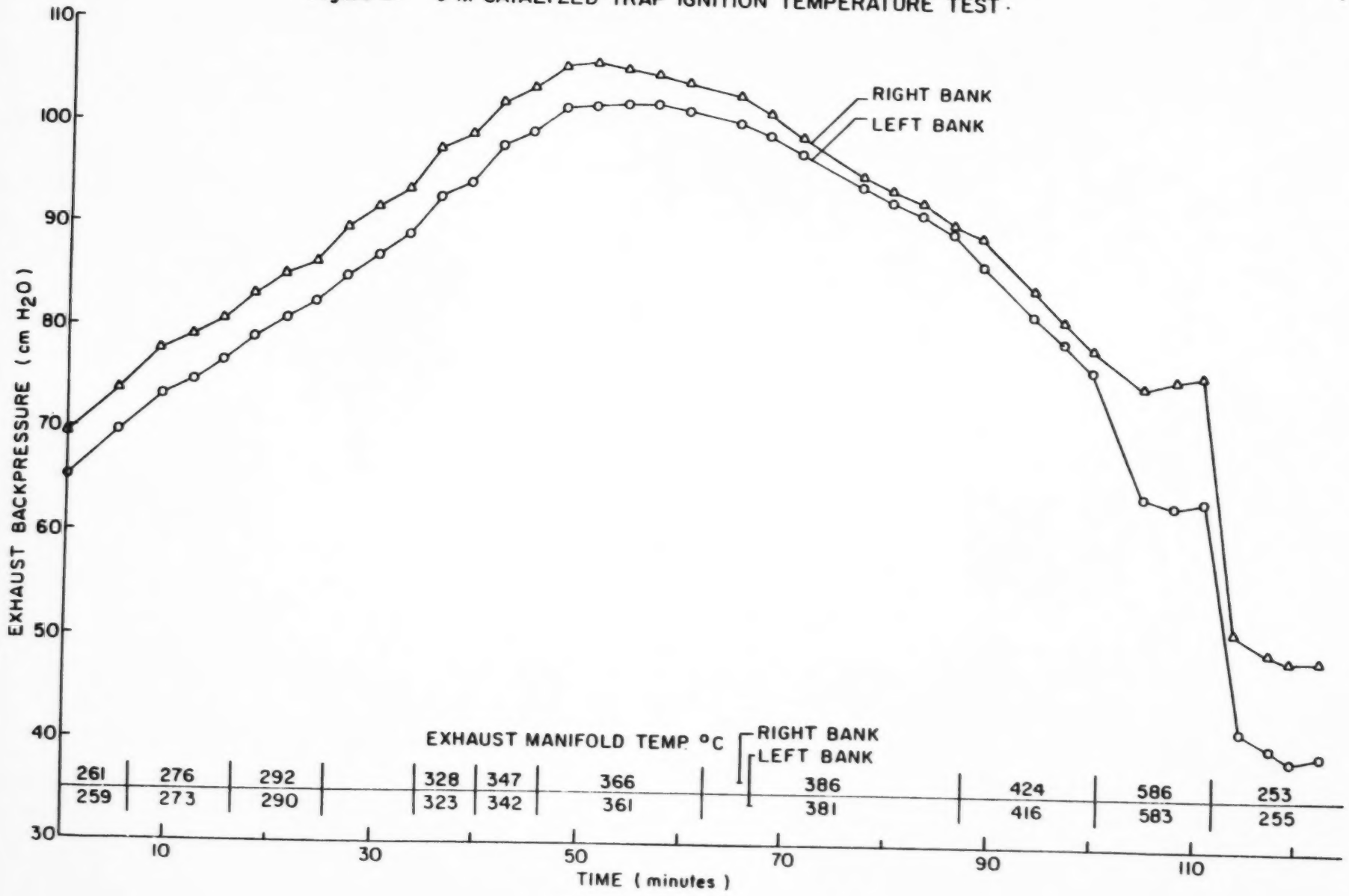


Figure 3 : J-M CATALYZED TRAP ΔP BUILDUP DURING EMISSION TESTS

TESTS PERFORMED ON MTU CYCLE
AVERAGE SPEED - 2165 rpm
TORQUE - 318 N-m
TEMP. - 335 °C

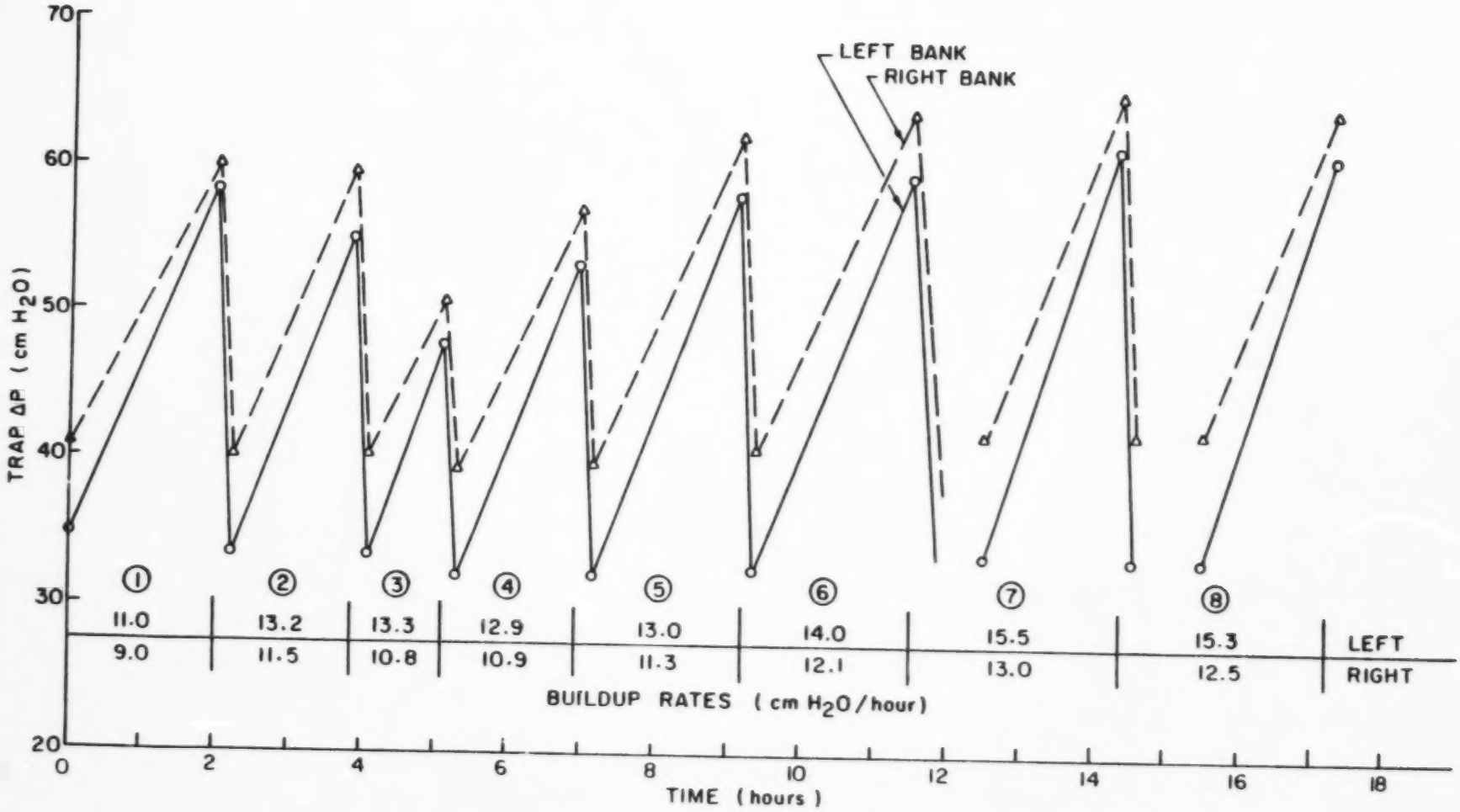


Figure 4 : J-M CATALYZED TRAP ENGINE BACKPRESSURES DURING EMISSION TESTS.

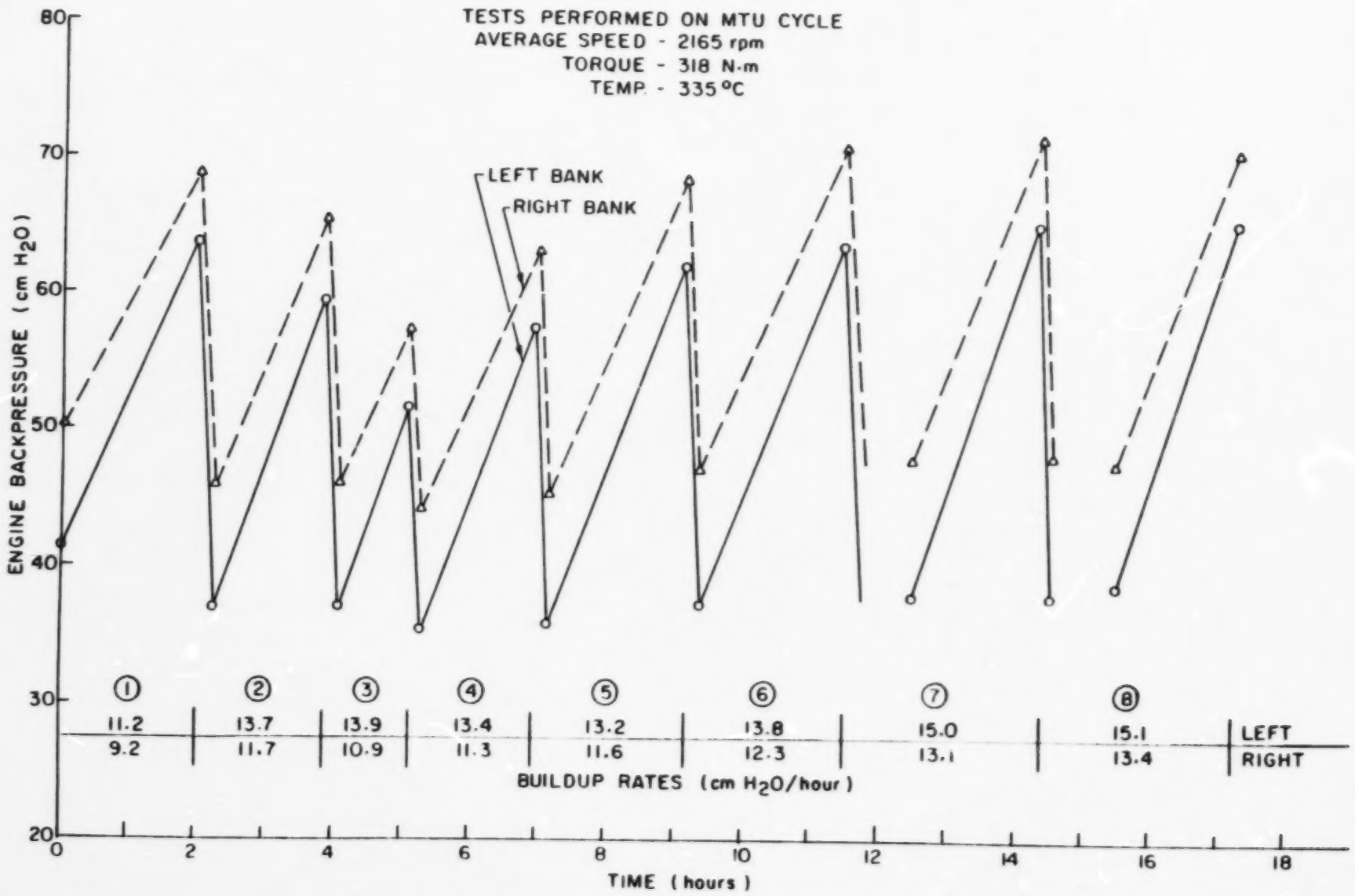


Figure 5: J-M CATALYZED TRAPS CARBON MONOXIDE CONCENTRATION DURING BURNOFF.

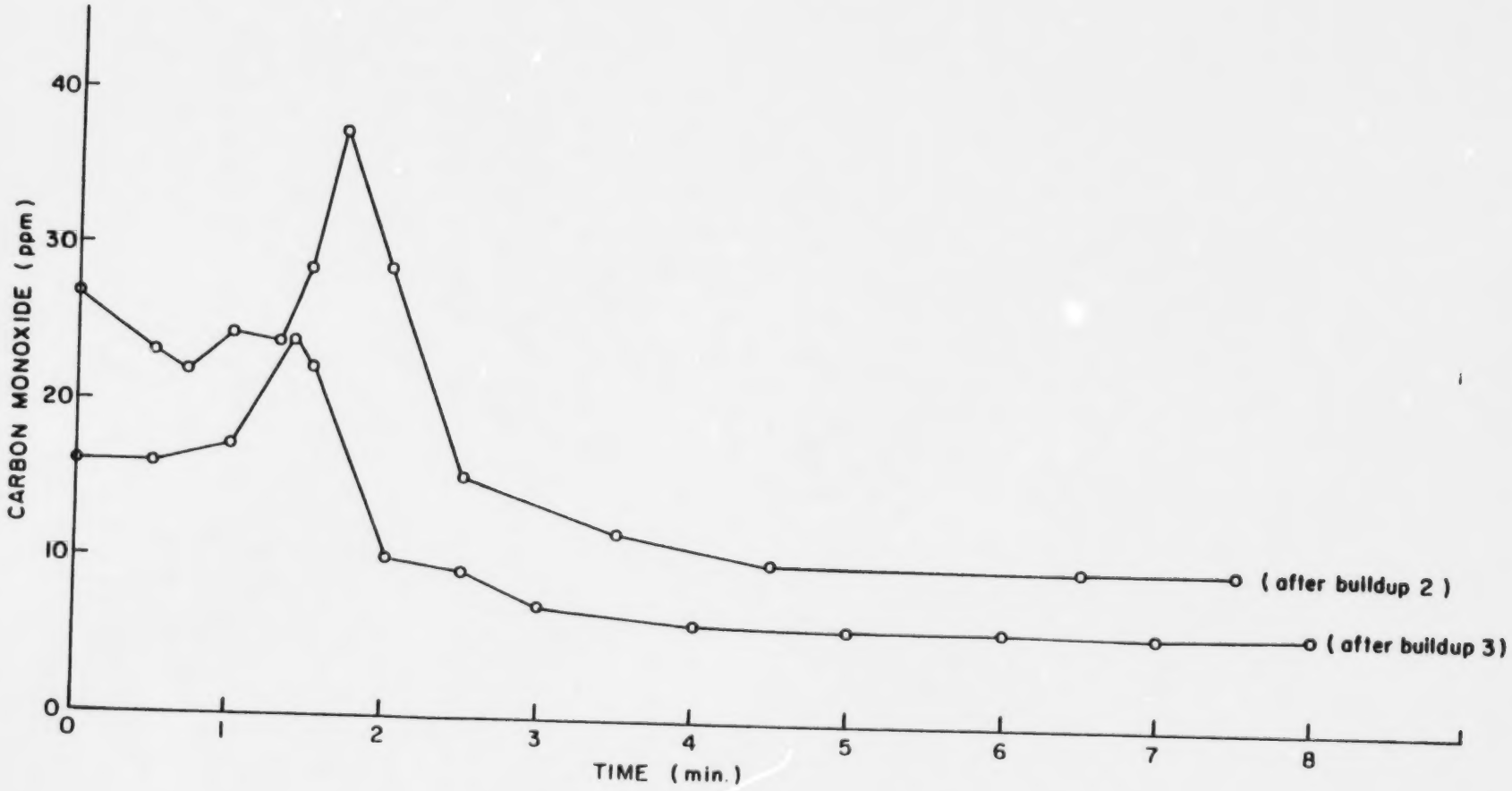
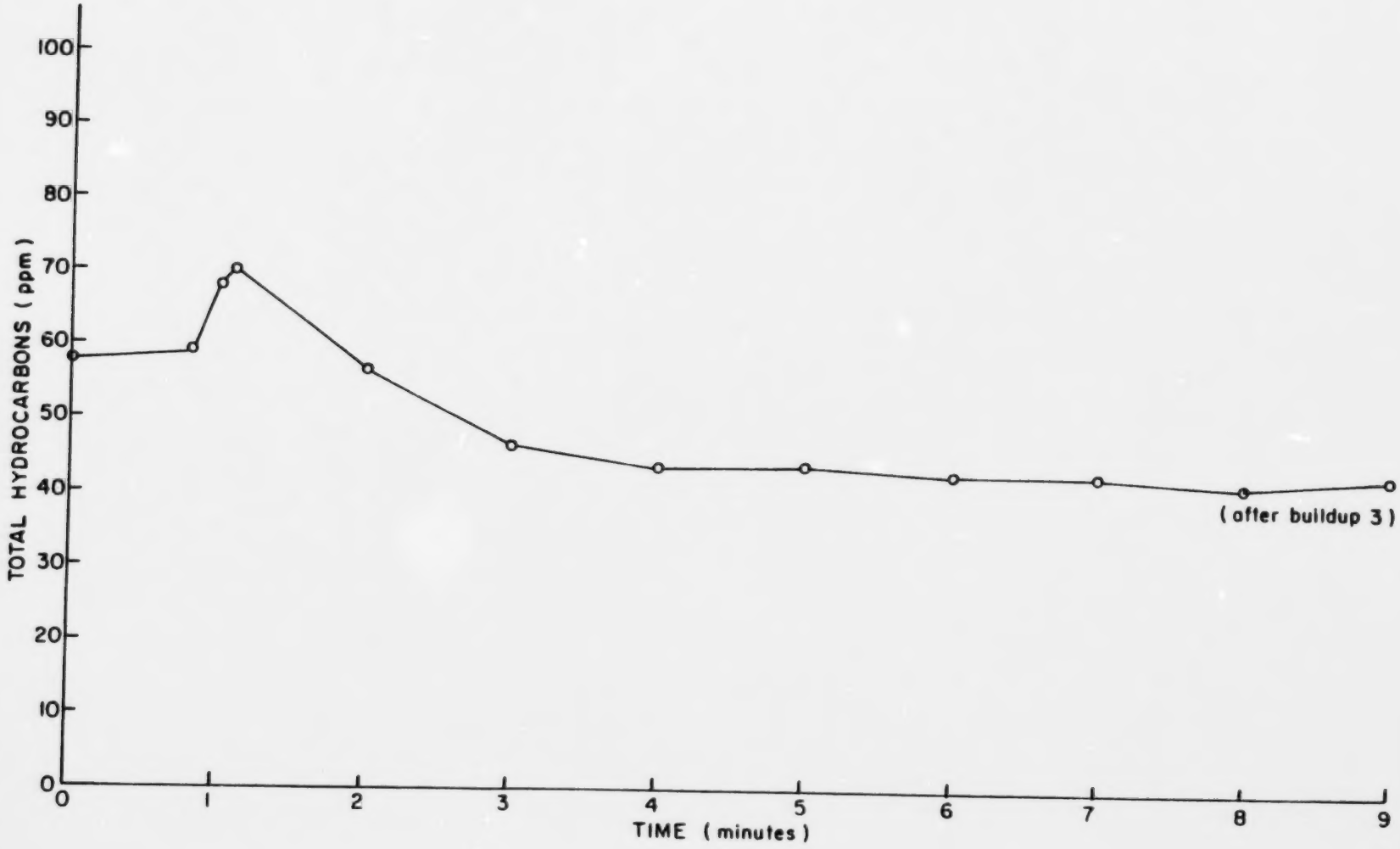


Figure 6: J-M CATALYZED TRAPS TOTAL HYDROCARBON CONCENTRATION DURING BURNOFF.



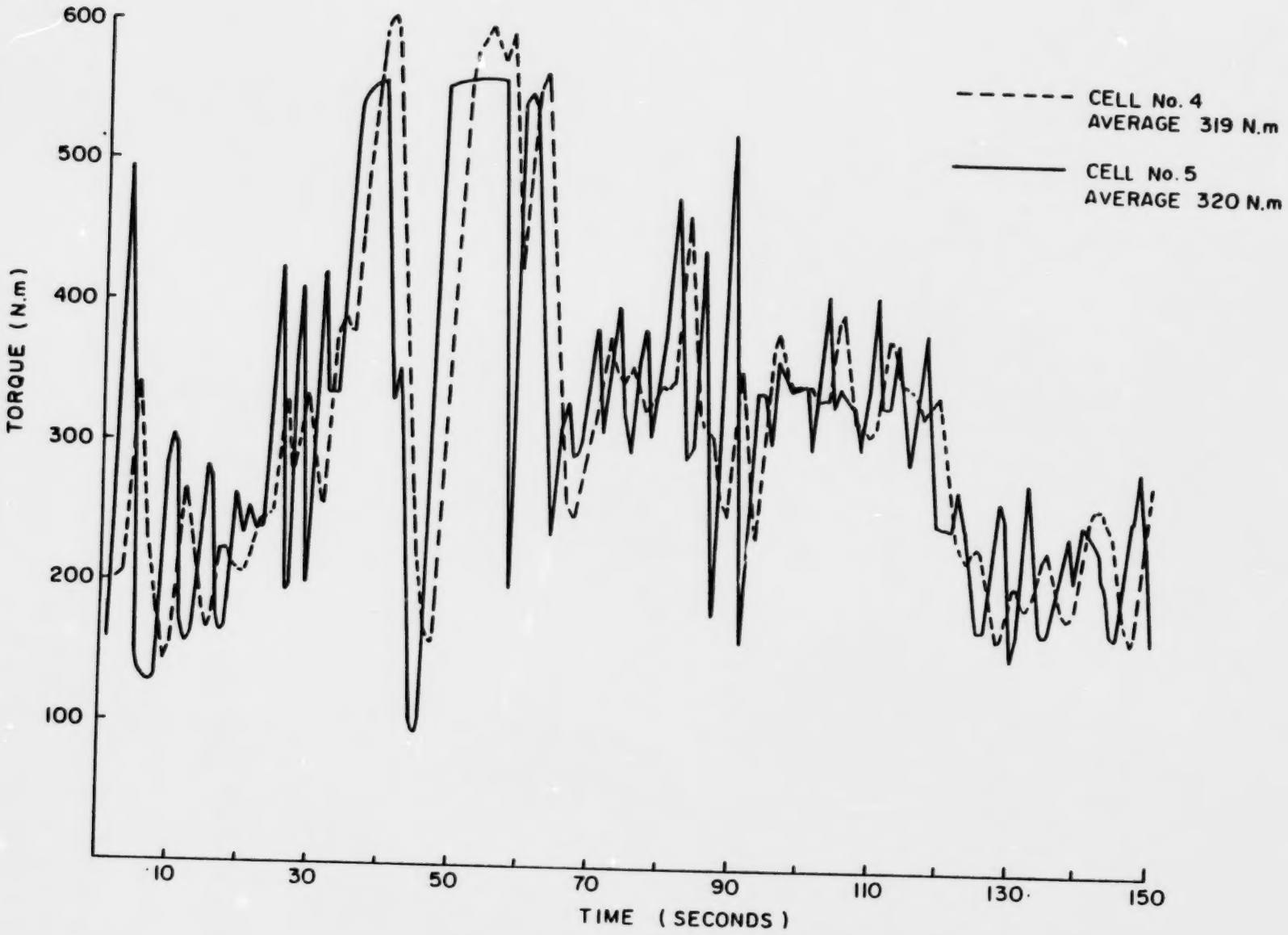


FIGURE 7. MTU-LHD CYCLE TORQUE COMPARISON

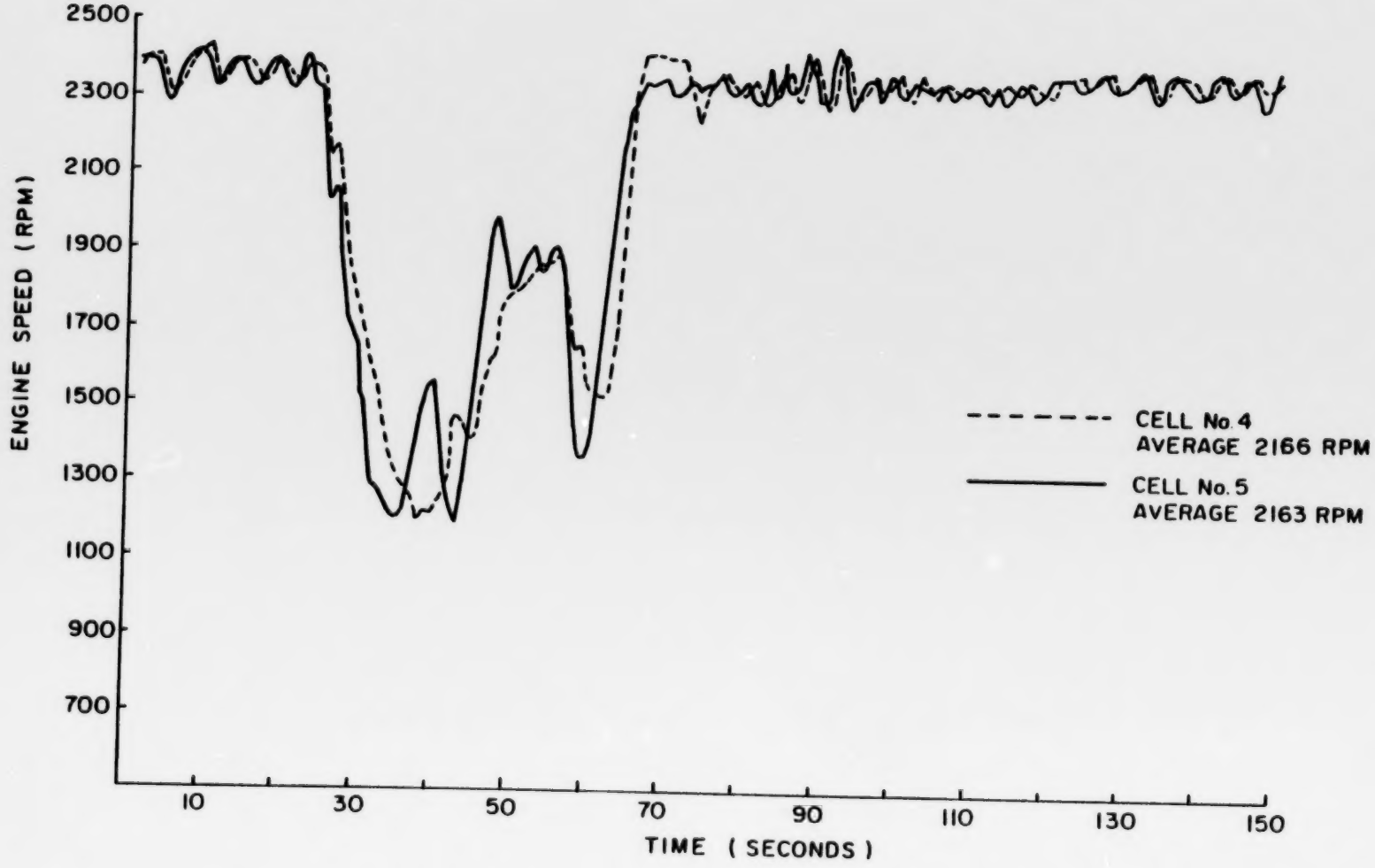


FIGURE 8 MTU-LHD CYCLE SPEED COMPARISON.